STRATEGIC ANALYSIS INC

H2A Case Overview: PEM Electrolysis for Hydrogen Production

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Case Overview

- Investigation of H_2 production using a standalone grid-powered polymer electrolyte membrane (PEM) electrolyzer
- Four cases developed using the H2A v3 tool (for high volume projections of H_2 production costs incorporating economies of scale) :

Case	Plant Start Date	Production of H_2 (kilograms (kg)/day)	Plant Life (years)
Current Forecourt	2010	1,500	20
Future Forecourt	2025	1,500	20
Current Central	2010	50,000	40
Future Central	2025	50,000	40

Current Case ("if you were fabricating today at production volume")*

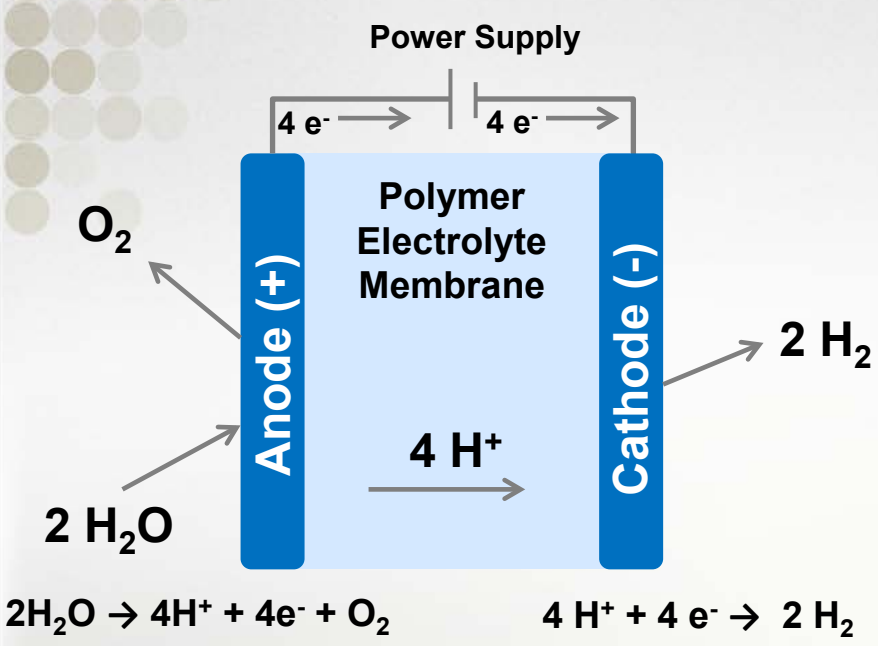
- Demonstrated advances in technology are implemented
- Potential reduction in capital cost from existing values
- Plant lifetimes consistent with measured or reported data

Future Case

- New materials and systems with increased H_2 production efficiency and longer plant lifetimes
- Improved replacement cost schedule
- Greater reductions in capital cost

**not to be confused with existing costs based on low production commercially available electrolyzers*

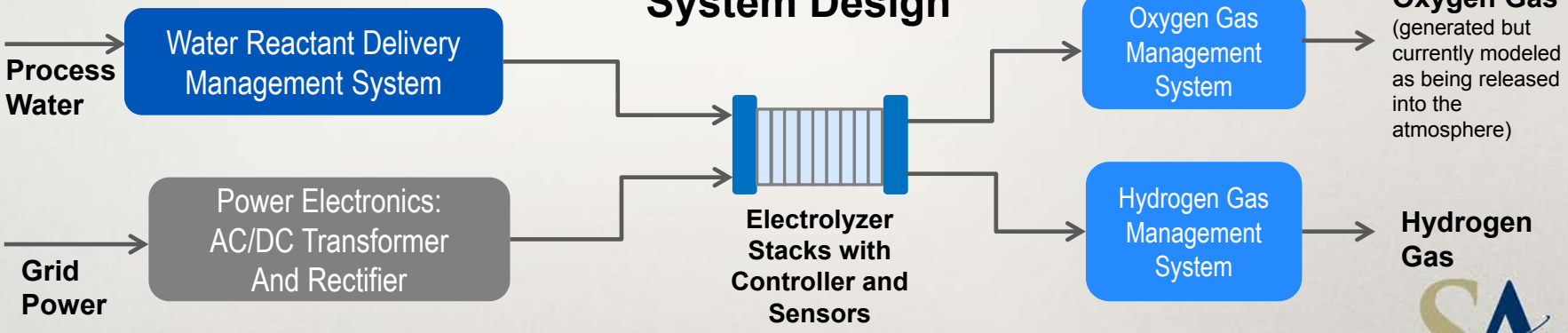
PEM Electrolysis Technology



PEM water electrolysis uses electrical power to split water into oxygen (O_2) and hydrogen (H_2).

- Positive terminal (anode): water (H_2O) reacts with catalyst to form oxygen molecules, electrons (e^-), and hydrogen protons (H^+).
- Electrolyte: hydrogen protons are conducted across the polymer electrolyte membrane.
- External circuit: electrons flow through an external power supply to produce an electric current.
- Negative terminal (cathode): the electrons combine with the hydrogen protons to produce H_2.

Hydrogen Production System Design



Key Analysis Modeling Assumptions and Basis for Assumptions

- **Summary:** PEM Electrolysis H2A case models based on a generic system using input from several key industry collaborators with commercial experience in PEM electrolysis.
- **Methodology:**
- Solicited information from four electrolyzer companies
- Requested relevant detailed information on:
  - Current/Future cases for Forecourt/Central
  - Followed H2A sheet input format:
    - System definition
    - Operating conditions
    - Variable and fixed expenses
    - Capital costs
    - Replacement costs
- Data synthesized, amalgamated into base parameters for cases
- Base parameters & sensitivity limits vetted by the four companies
- Four H2A cases populated and models run to predict H_2 cost
  - Current/Future cases for Forecourt/Central production

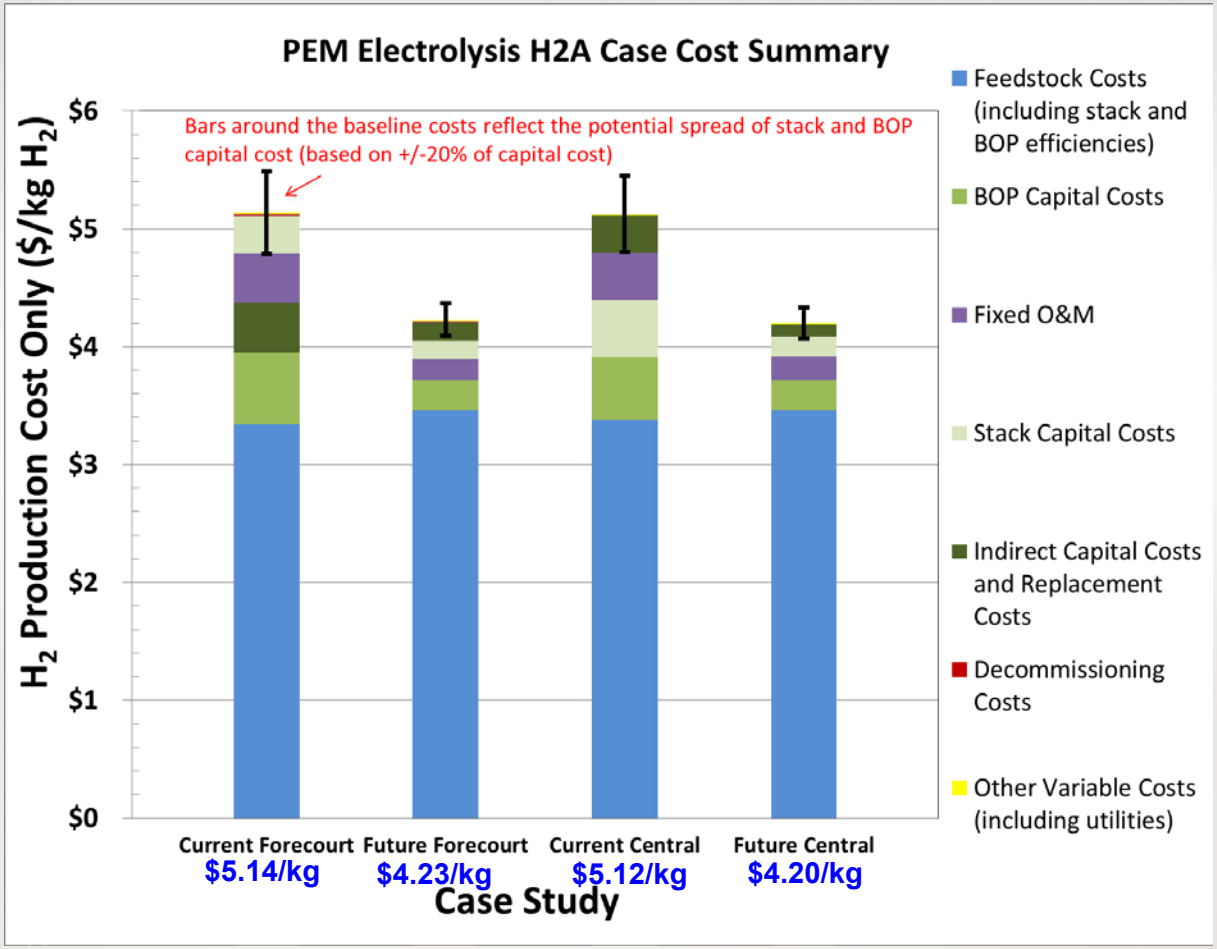
PEM Electrolyzer System Performance Parameters

Parameter	Current Forecourt	Future Forecourt	Current Central	Future Central
Levelized Cost of H_2 (2007$/kg H_2)	$5.14	$4.23	$5.12	$4.20
Plant Capacity (kg day)	1,500	1,500	50,000	50,000
Total Uninstalled Capital (2012$/kW)	$940	$450	$900	$400
Stack Capital Cost (2012$/kW)	$385	$173	$421	$150
BOP Capital Cost (2012$/kW)	$555	$277	$479	$250
Total Electrical Usage (kWh/kg) (% LHV H_2)	54.6 (61%)	50.3 (66%)	54.3 (61%)	50.2 (66%)
Stack Electrical Usage (kWh/kg)	49.2 (68%)	46.7 (71%)	49.2 (68%)	46.7 (71%)
BOP Electrical Usage (kWh/kg)	5.4	3.7	5	3.5
Electrolyzer Power Consumption (MW)	3.4	3.1	113	104.6
Average Electricity Price[1] (2007¢/kWh)	6.12	6.88	6.22	6.89
Electricity Price in Startup Year [2] (H2A Default Values) (2007¢/kWh)	5.74	6.59	5.74	6.59
Hydrogen Outlet Pressure (psi)	450	1,000	450	1,000
Installation Cost (% of Total Capital)	12%	10%	12%	10%
Replacement Interval (years)	7	10	7	10
Replacement Cost of Major Components (% of installed capital cost)	15%	12%	15%	12%

[1] Average electricity price over life of plant (20 years for Forecourt cases and 40 years for Central cases)

[2] H2A default values from Energy Information Administration (EIA) Annual Energy Outlook (AEO) data.

PEM Electrolysis H2A Case Production Cost Results*



** In a 2007 dollar cost basis, standard to the H2A v3 tool (reflecting production costs only)*

- All cases reflect a $4-$5/kg cost for H_2 production. The current cases ($5.14 vs. $5.12) and the future cases ($4.23 vs. $4.20) are similar in cost.
- The H_2 cost reduction is greater moving from a current to a future case, compared with moving from a forecourt to a central case.
- Feedstock costs (electricity expenditures) are 65%-80% of total costs (using average electricity prices between 6.12-6.89 (2007¢/kWh)).
- To reduce cost: increase efficiency and decrease electricity price.

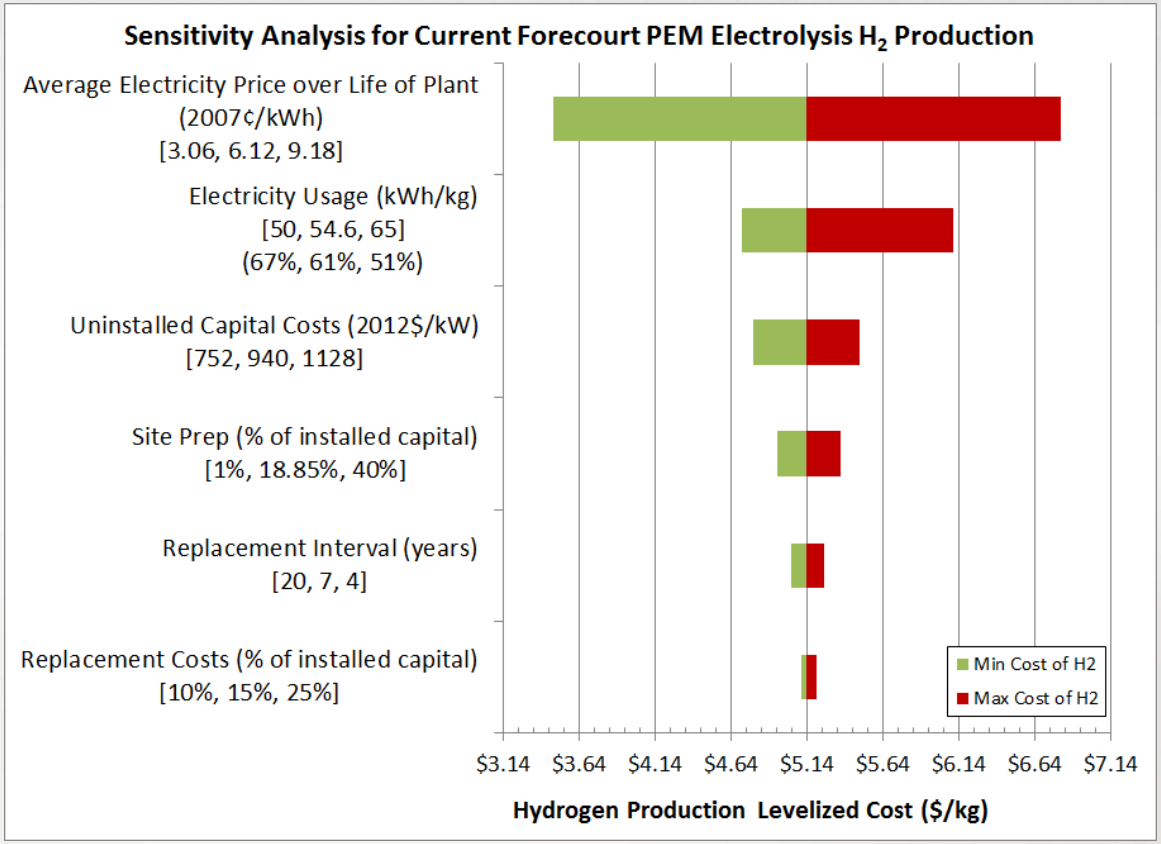
Discussion of Cost Drivers

- H2A PEM Electrolysis cases show production costs are highly dependent on (1) electricity price, (2) electrolyzer efficiency, and (3) electrolyzer capital cost.

1. Electricity Price (¢/kWh)
   a. Based on Annual Energy Outlook (AEO) reference tables or DOE target values
   b. Not governed by PEM electrolysis technology (although relates to electrical efficiency)
2. Electrical Efficiency (kWh/kg H_2)
   a. Stack efficiency based on operating voltage and H_2 permeation losses
   b. BOP efficiency based on power inverter module, rectifier, and dryer efficiencies
   c. SA selected stack operating points based on industry feedback for PEM electrolyzer: Capital Cost ($)
   d. Methodology: Compared and contrasted industry data. Then used a weighted average of individual components based on company stack, balance of plant, and system production experience.
   e. The quality of the PEM electrolysis industry feedback facilitated providing greater detail in the cost breakdown for systems and reflects a more accurate, albeit higher, capital cost for PEM electrolyzers than in previous published H2A electrolyzer analyses.

7

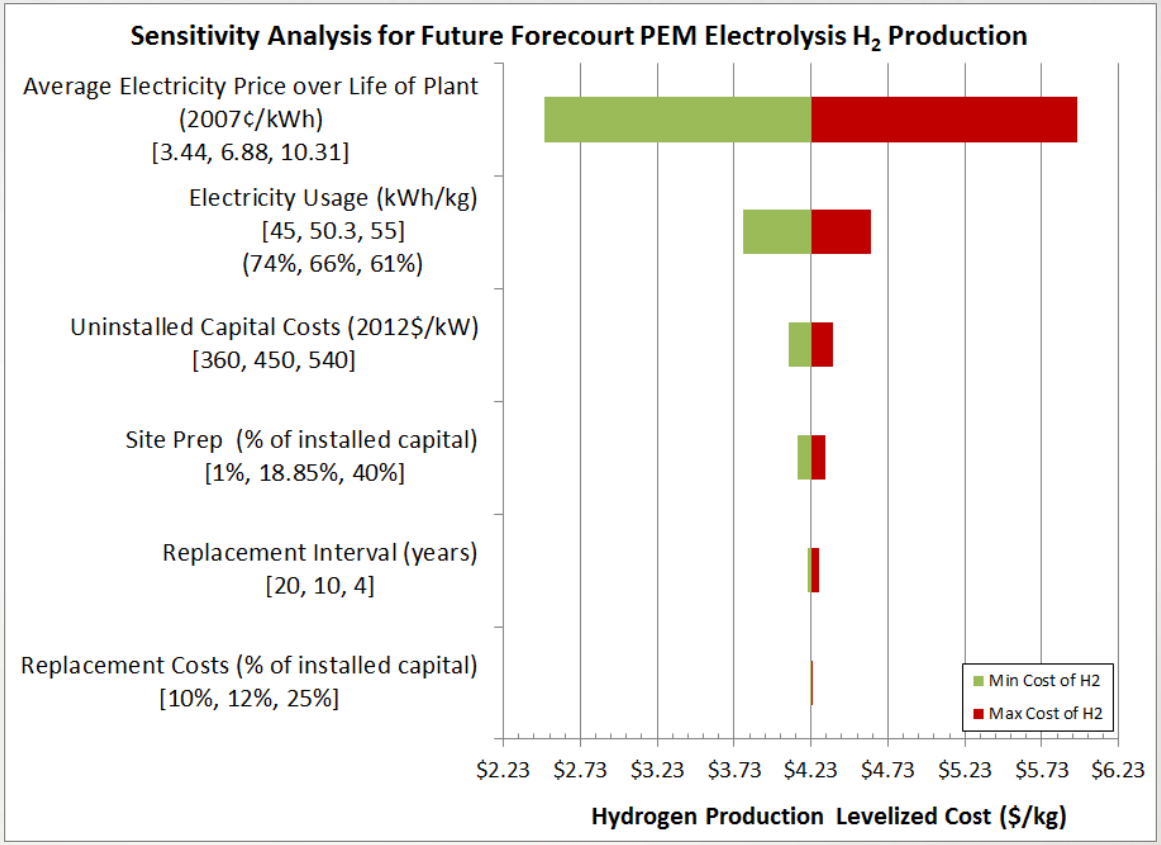
Sensitivity Analysis: Current 2010 Forecourt Technology Projection



Parameter values used within the tornado chart

Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.06¢/kWh	$3.47	6.12¢/kWh	$5.14	9.18¢/kWh	$6.81
Electricity Usage (% LHV H_2)	50kWh/kg (67%)	$4.71	54.6kWh/kg (61%)	$5.14	65kWh/kg (51%)	$6.11
Uninstalled Capital Costs	$752/kW	$4.79	$940/kW	$5.14	$1,128/kW	$5.49
Site Prep	1%	$4.95	18.85%	$5.14	40%	$5.36
Replacement Interval	20yr	$5.04	7yr	$5.14	4yr	$5.25
Replacement Costs	10%	$5.11	15%	$5.14	25%	$5.20

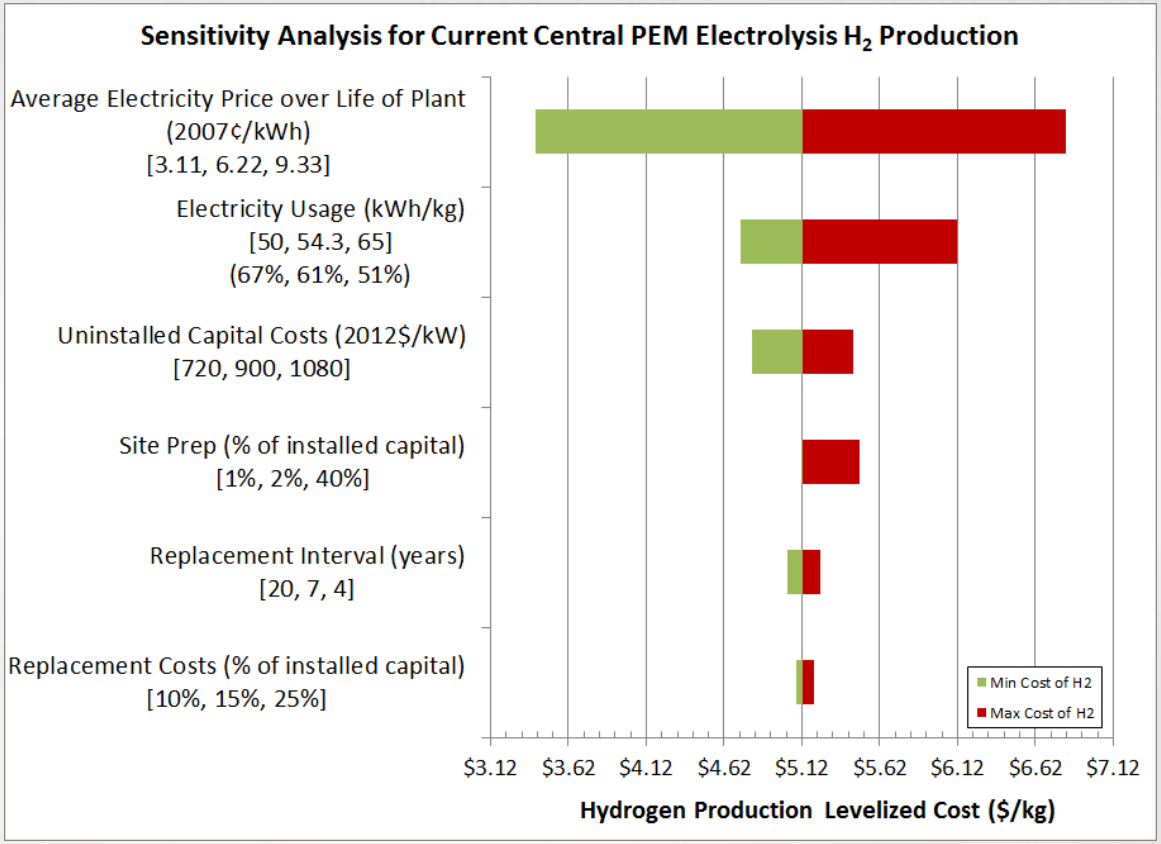
Sensitivity Analysis: Future 2025 Forecourt Technology Projection



Parameter values used within the tornado chart

Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.44¢/kWh	$2.50	6.88¢/kWh	$4.23	10.31¢/kWh	$5.96
Electricity Usage (% LHV H_2)	45kWh/kg (74%)	$3.79	50.3kWh/kg (66%)	$4.23	55kWh/kg (61%)	$4.62
Uninstalled Capital Costs	$360/kW	$4.08	$450/kW	$4.23	$540/kW	$4.37
Site Prep	1%	$4.14	18.85%	$4.23	40%	$4.32
Replacement Interval	20yr	$4.21	10yr	$4.23	4yr	$4.28
Replacement Costs	10%	$4.22	12%	$4.23	25%	$4.24

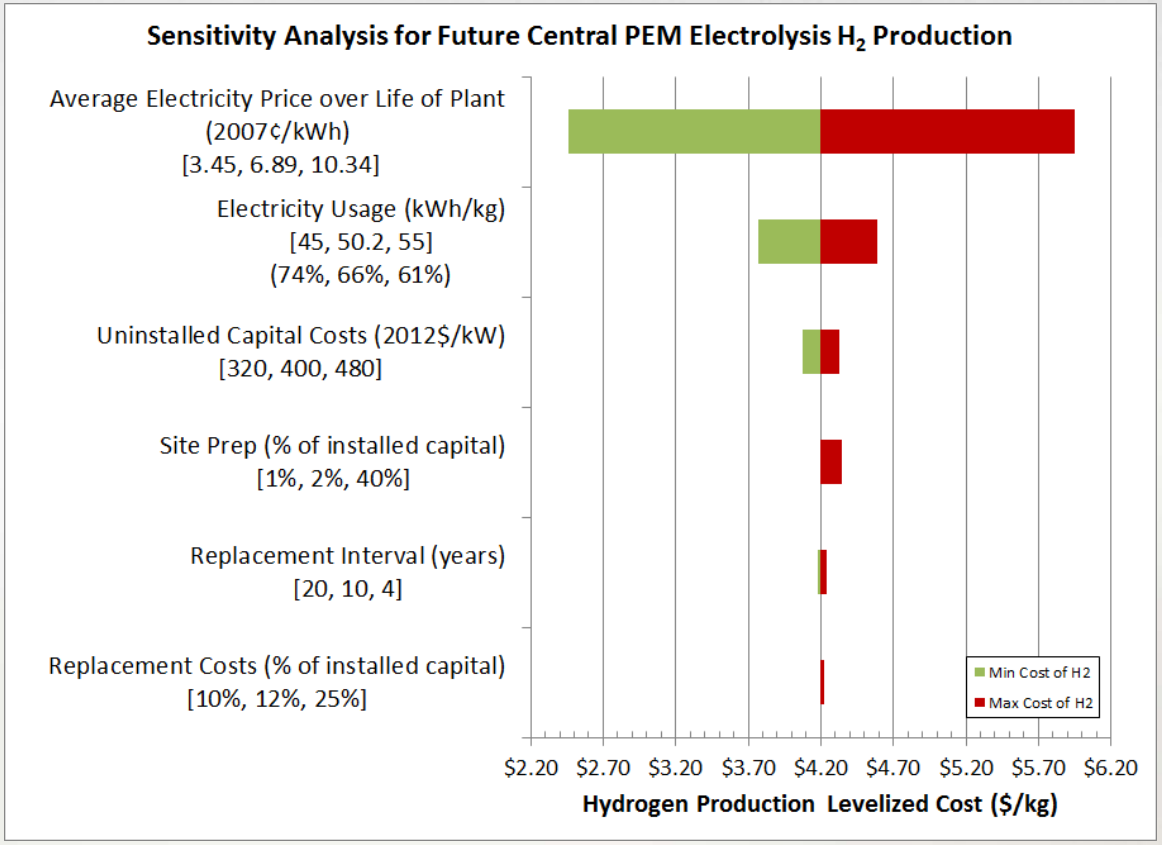
Sensitivity Analysis: Current 2010 Central Technology Projection



Parameter values used within the tornado chart

Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.11¢/kWh	$3.41	6.22¢/kWh	$5.12	9.33¢/kWh	$6.82
Electricity Usage (% LHV H_2)	50kWh/kg (67%)	$4.72	54.3kWh/kg (61%)	$5.12	65kWh/kg (51%)	$6.12
Uninstalled Capital Costs	$720/kW	$4.80	$900/kW	$5.12	$1080/kW	$5.45
Site Prep	1%	$5.11	2%	$5.12	40%	$5.49
Replacement Interval	20yr	$5.03	7yr	$5.12	4yr	$5.24
Replacement Costs	10%	$5.09	15%	$5.12	25%	$5.20

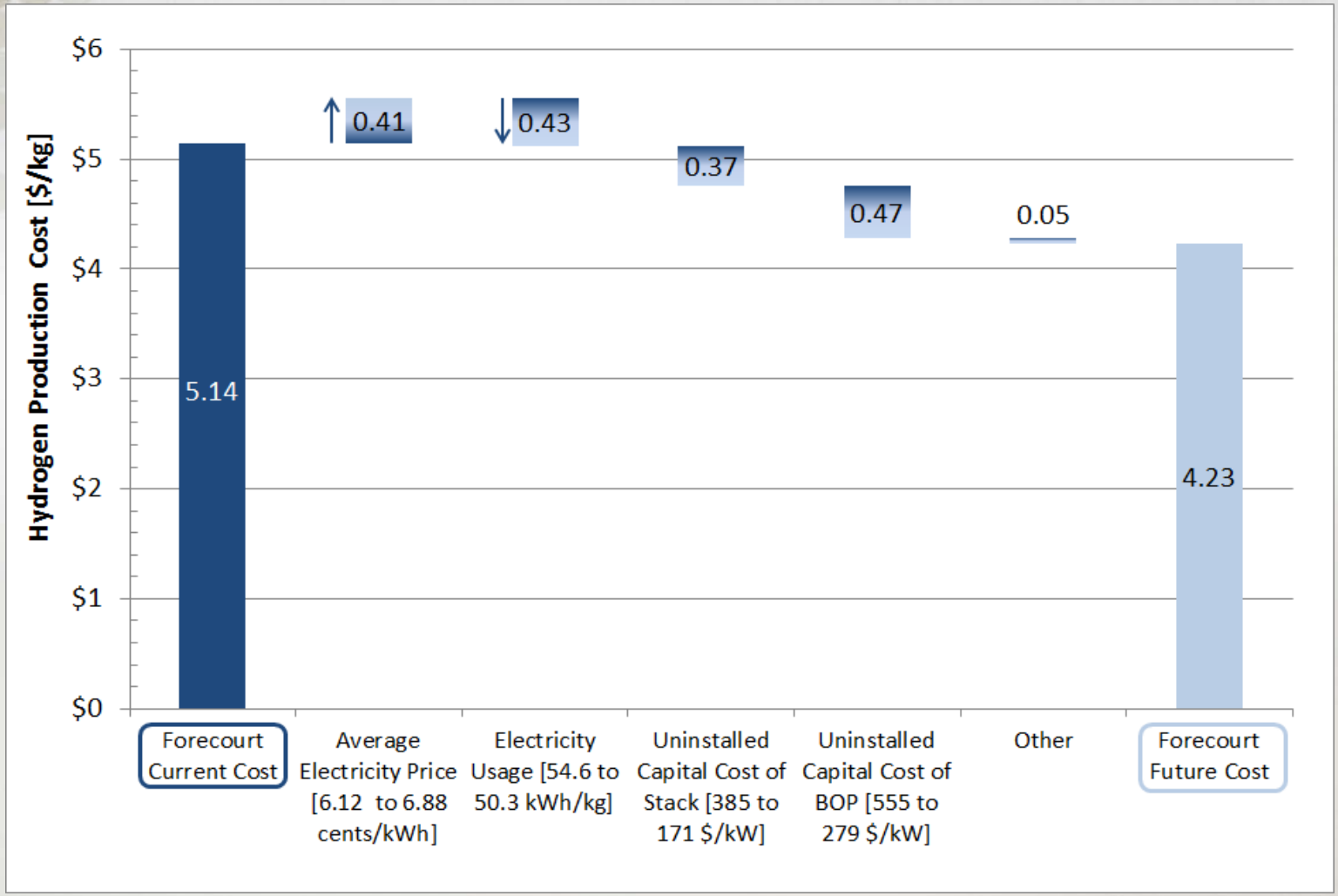
Sensitivity Analysis: Future 2025 Central Technology Projection



Parameter values used within the tornado chart

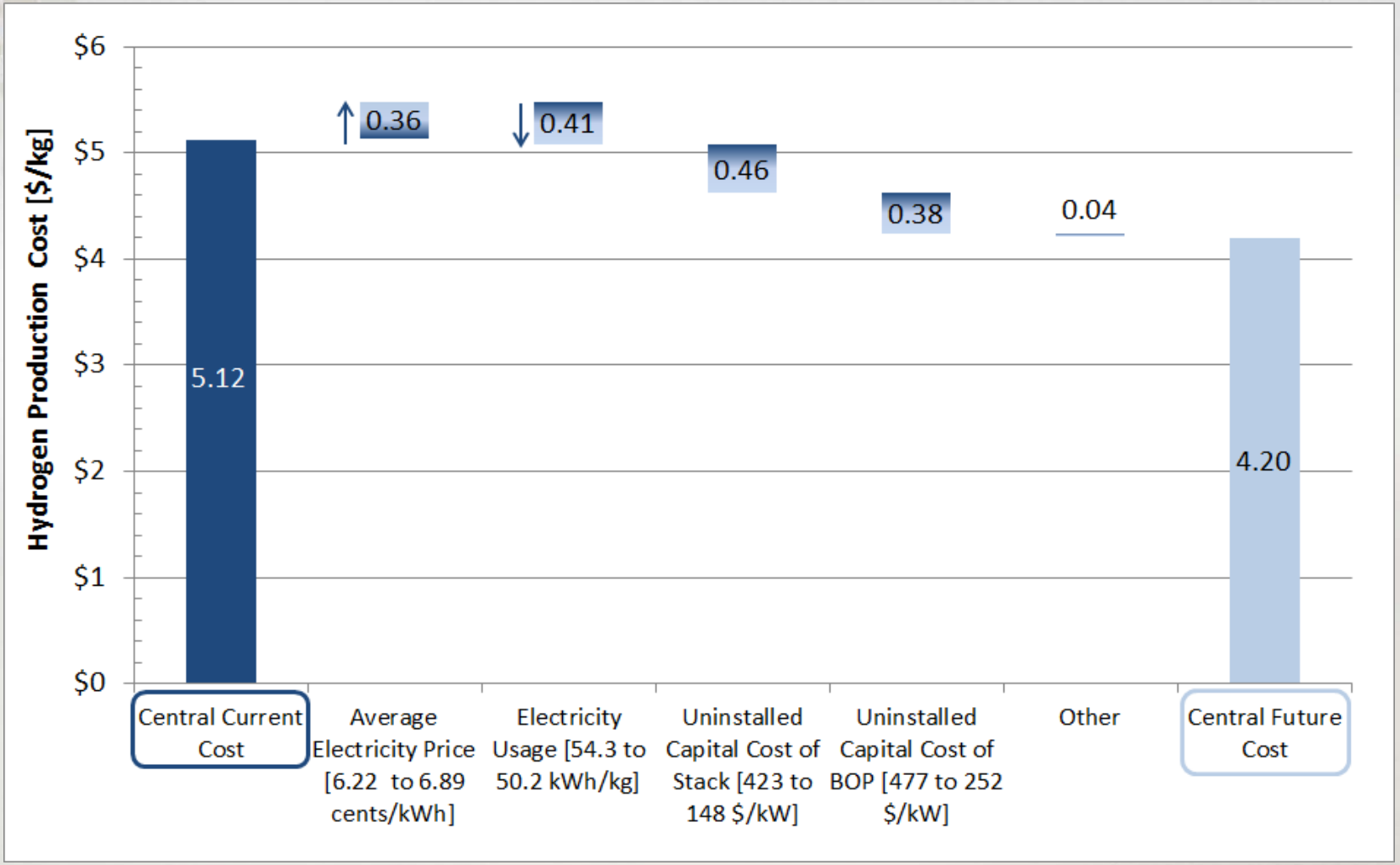
Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.45¢/kWh	$2.46	6.89¢/kWh	$4.20	10.34¢/kWh	$5.95
Electricity Usage (% LHV H_2)	45kWh/kg (74%)	$3.77	50.2kWh/kg (66%)	$4.20	55kWh/kg (61%)	$4.59
Uninstalled Capital Costs	$320/kW	$4.07	$400/kW	$4.20	$480/kW	$4.33
Site Prep	1%	$4.19	2%	$4.20	40%	$4.35
Replacement Interval	20yr	$4.18	10yr	$4.20	4yr	$4.24
Replacement Costs	10%	$4.19	12%	$4.20	25%	$4.22

Waterfall Chart: Forecourt Current to Future



Although electricity price increases between current (6.12¢/kWh) and future (6.88¢/kWh) cases, electrical efficiency rises (3rd column), thereby reduces net electricity expenditures, and brings the levelized cost of H_2 down. "Other" refers to the changes in replacement interval, replacement cost, installation cost factor, and production maintenance and repairs.

Waterfall Chart: Central Current to Future



Similar results are seen for the Central cases between current to future.

Publicly Available Sources/References

- Independent Review: Current (2009) State of the Art Hydrogen Production Cost Estimate Using Water Electrolysis
  - http://www.hydrogen.energy.gov/pdfs/46676.pdf
- 2013 H2A Case Overview Presentation of PEM Electrolysis Hydrogen Production
  - http://www.hydrogen.energy.gov/h2a_production_documentation.html
- PEM Electrolysis H2A Production Case Study Documentation
  - http://www.hydrogen.energy.gov/h2a_production_documentation.html
  - Includes data questionnaire sent to the four companies
  - Includes base parameters and sensitivity limits of four cases
- Four H2A cases on PEM Electrolysis
  - http://www.hydrogen.energy.gov/h2a_prod_studies.html